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On carrier spillover in c- and m-plane InGaN light emitting diodes

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The internal quantum efficiency (IQE) and relative external quantum efficiency (EQE) in InGaN light-emitting diodes (LEDs) emitting at 400 nm with and without electron blocking layers (EBLs) on c-plane GaN and m-plane GaN were investigated in order to shed some light on any effect of polarization charge induced field on efficiency killer carrier spillover. Without an EBL the EQE values suffered considerably (by 80%) for both orientations, which is clearly attributable to carrier spillover. Substantial carrier spillover in both polarities, therefore, suggests that the polarization charge is not the major factor in efficiency degradation observed, particularly at high injection levels. Furthermore, the m-plane variety with EBL did not show any discernable efficiency degradation up to a maximum current density of 2250 A cm^{-2} employed while that on c-plane showed a reduction by ~40%. In addition, IQE of m-plane LED structure determined from excitation power dependent photoluminescence was ~80% compared to 50% in c-plane LEDs under resonant and moderate excitation condition. This too is indicative of the superiority of m-plane LED structures, most probably due to relatively larger optical matrix elements for m-plane orientation. © *2009 American Institute of Physics*. [doi:10.1063/1.3266833]

Since the demonstration of commercially viable blue light-emitting diodes (LEDs) using nitride-based materials,[1] there has been steady improvement in material quality and device fabrication/packaging to the point that the nitride semiconductor based LEDs are being considered for general lighting applications. Despite substantial progress, the so called "efficiency droop"[2] is hindering high brightness LEDs, which must be overcome before widespread applications in general could become possible. Fuelled by interest in the problem, many proposals have been forwarded to explain this phenomenon. Among them are, "current rollover,"[3] inefficient carrier injection,[4] Auger recombination,[5] and polarization field.[6] It should be noted, however, that Auger coefficient in wide bandgap materials is expected to be very small.[7] Furthermore, AlInGaN barriers employed in multiple quantum well structures to reduce the polarization charge did not appear to have much of an effect on efficiency droop[8] whereas modifying the quantum well structure (reduced barrier thickness and p-doping in barriers) did,[9,10] This raises the question whether the polarization charge induced field is the main or at least a major mechanism responsible for efficiency degradation.

In the present study, we investigated LEDs on m-plane bulk GaN substrates, which are polarization induced field free, and also on c-plane GaN, which has polarization field, in order to interrogate any effect the polarization induced field may have on efficiency and efficiency retention at increased injection levels. In this realm we conducted excitation power dependent photoluminescence (PL) and pulsed electroluminescence (EL) experiments. The EL experiments clearly show that both c- and m-plane LEDs exhibit very low relative external quantum efficiencies (EQEs) when an electron blocking layer (EBL) is not employed. However, resonant excitation data, intended to probe the internal quantum efficiency (IQE), seem to show that LED structures with and without EBL are comparable, implying that electrical injection and the associated phenomena are responsible for efficiency reduction/degradation. Furthermore, m-plane LEDs with EBL did not show efficiency degradation at high injection levels whereas those on c-plane did. The data also indicate that the LEDs on both types of substrates and without EBLs are free of efficiency degradation at high injection levels to a large degree as carrier spillover is dominant in the absence of EBLs.

The c- and m-plane InGaN MQW LEDs investigated were grown on c-plane GaN templates on sapphire and on m-plane bulk wafers using a vertical low pressure metalorganic chemical vapor deposition system. The 500 μm-thick m-plane GaN wafers, produced at Kyma Technologies, Inc., using hydride vapor phase epitaxy growth along the c-direction followed by slicing perpendicular to the surface, have a threading dislocation density of $<5\times10^6$ cm^{-2} and are off-cut by 0.2° toward the GaN a-axis and 0.3° toward the GaN c-axis. The threading dislocation density for the c-plane templates prepared with 3 μm-thick GaN grown on sapphire is 2×10^8 cm^{-2}. To improve the material quality a 60-nm-thick Si-doped (2×10^{18} cm^{-3}) $In_{0.01}Ga_{0.99}N$ underlayer was included just below the active region consisting of six periods of 2-nm-thick $In_{0.14}Ga_{0.86}N$ quantum wells (QWs) and 12-nm-thick $In_{0.01}Ga_{0.99}N$ barriers. Subsequently, a ~10-nm-thick Mg-doped p-$Al_{0.15}Ga_{0.85}N$ EBL was employed on top of the active region in samples which incorporated this feature. The thickness of the p-GaN layer that followed, having a hole concentration of more than 7×10^{17} cm^{-3} upon activation (measured for a test sample on c-plane GaN/sapphire template), was 100 nm. As for the LED device fabrication, 250-μm-diameter mesas were

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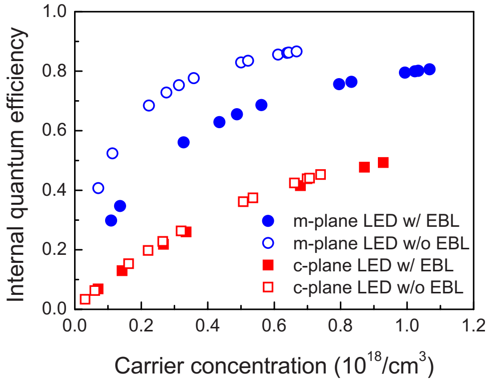

FIG. 1. (Color online) IQE values of c- and m-plane LEDs with and without EBL vs the induced carrier concentration calculated from the resonant PL measurements using excitation power-dependence. For the calculation of carrier concentrations, the radiative recombination coefficient B was assumed to be 1×10^{-11} cm^3 s^{-1}.

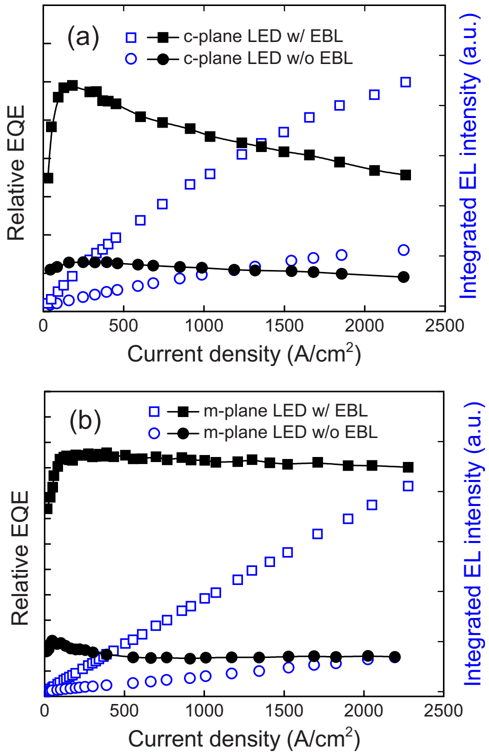

FIG. 2. (Color online) Relative EQE (solid symbols) and light intensity (open symbols) values of (a) c-LEDs and (b) m-LEDs with and without EBL as a function of current density applied by a 0.1% duty cycle pulsed current source.

formed using inductively coupled plasma reactive ion etching. After deposition of Ti/Al/Ni/Au (30/100/40/50 nm) for n-type ohmic contacts, the metal stack was annealed at 800 °C for 60 s while very thin Ni/Au (5/5 nm) was used for semi-transparent p-contacts and 30/50 nm Ni/Au for contact pads on part of the mesa tops. See Ref. 10 for details of the device structures.

In order to determine the IQE excitation dependent resonant PL measurements were conducted at room temperature using 370 nm excitation from a frequency-doubled 80 MHz mode-locked femtosecond Ti:sapphire laser. Figure 1 shows the IQE values of all LED samples versus the generated carrier concentration calculated from the resonant PL measurements.[11] Selection of the particular excitation source wavelength was motivated by generation of electron-hole pairs only inside the QWs, which served to avoid carrier generation in barriers and helped mitigate data analysis. The IQE values of c-plane LEDs with and without an EBL have very similar values over the entire range of carrier concentrations up to 1×10^{18} cm^{-3}, at which a value of ∼50% is reached. This similarity in the IQE values is indicative of the fact that the resonant carrier excitation causes electron-hole pair generation only inside MQWs, where they also undergo radiative recombination, and therefore, the EBL has no effect on the IQE. In comparison, the IQE values for m-plane LED structures are much higher reaching slightly above 85% for the structure without the EBL layer and a comparable value of ∼80% for the one with EBL at steady state carrier concentrations of 7×10^{17} and 1×10^{18} cm^{-3}, respectively. The main difference between the two m-plane LED MQW structures is the steeper increase in IQE with carrier density in the one without the EBL due to lower nonradiative Shockley–Read–Hall recombination. This is attributed to the variation in the material quality in the two structures, arising mainly from the variations in the quality of the m-plane bulk substrates. Obviously, when compared to the c-plane structures investigated here the m-plane LED structures are expected to have better material quality, therefore higher IQE (Fig. 1), as they are grown on native GaN substrates. Furthermore, LEDs of the same structure fabricated on freestanding c-plane GaN substrates have also been shown to exhibit IQE values inferior to those of the m-plane LEDs.[12] Therefore, beyond the improved quality of the m-plane variety, the relatively larger optical matrix elements predicted for m-plane might in part be responsible for improved quantum efficiency for m-plane.[13]

The relative EQEs for both c- and m-plane LEDs were determined from EL spectra using a pulsed current source with 0.1% duty cycle and 1 kHz frequency in order to eliminate the heating effect. Photon extraction efficiencies of compared devices are assumed to be the same as we employed the same fabrication procedure without any dicing or packaging involved. Figures 2(a) and 2(b) show relative EQE values and light intensity versus current density of all LED samples, inclusive of LEDs with and without EBL layers on sapphire and m-plane GaN. The salient difference between LEDs with EBL on m-plane bulk GaN and c-plane templates is that those on c-plane substrates exhibit substantial efficiency degradation, by ∼40%, as compared to negligible degradation on m-plane with increasing current density up to 2250 A cm^{-2}.

The striking observation is that both c-plane and m-plane LEDs without EBL suffered from severe efficiency degradation. The efficiency on the m-plane variety shows a peaklike feature at approximately 100 A cm^{-2} and settles rather quickly to a constant value up the maximum current density of 2250 A cm^{-2}. The nature of this peak is still under investigation. Overall, the peak efficiency is only about 20% of that observed in the structure with an EBL. This clearly indicates that even without the polarization induced field in the QW active region, the spillover of carriers, most likely electrons, is severe. The structure without EBL on c-plane variety also undergoes severe efficiency degradation, by some 80% (peak efficiency), as compared to the structure with an EBL. Strikingly absent is the further degradation of the efficiency with injection current unlike the case with the EBL layer on c-plane GaN. This is somewhat expected as majority of the injected electrons flow over the active region into the p-GaN layer with very low radiative recombination efficiency, resulting in relatively low but steady EQE with increased injection.

The EL data indicate that regardless of whether polarization induced electric field exists or not, the carrier spillover is a very serious impediment to efficiency. However, all optical measurements indicate hardly any dependence on the EBL in terms of the ultimate efficiency both on m-plane and also the c-plane varieties. This means that when the carriers are generated optically only in the QWs in equal quantities, they recombine either nonradiatively only in the active region, which is noticeable more at low excitation levels, or radiatively which is dominant at high excitation levels. In contrast, when the carriers, both holes and electrons, are injected electrically by a p-n junction, the carrier spillover is severe in LEDs without the EBLs at high injection, i.e., a large amount of the injected electrons do not take part in any recombination process inside the active region QWs. Considering that both the m-plane variety without polarization charge induced electric field and the c-plane variety with polarization charge suffer substantial reduction in relative EQE, one can deduce that the carrier spillover is not necessarily a result of only the polarization field. Furthermore, since the relative EQE remains nearly constant for most of the current range investigated in the m-plane variety, one can argue that the spillover is linearly proportional to the current.

Our observations serve to shed light on and to help understand and control the possible sources responsible for carrier spillover. It is clear that electrons, being more mobile and abundant as compared to holes, would traverse to the p-layer unless the recombination paths and rates in the active region, both radiative and nonradiative, prevent this process. Possible remedies include increased p-doping on the p-side and reduced n-doping on the n-side. The positive effect of the latter has already been demonstrated.[10] Obviously further investigations are needed to unequivocally determine the driving force for carrier spillover and measures to reduce it if not totally eliminate it.

In conclusion, we investigated InGaN LEDs with and without electron blocking layers having 6×12 nm barrier/2 nm QW active regions grown on c-plane GaN templates and m-plane GaN bulk wafers with specific interest in the relative external efficiency and its degradation with injection current. With EBLs, the m-plane variety nearly fully retained its efficiency up to the maximum current density of 2250 A cm^{-2} while that on the c-plane exhibited efficiency reduction by some 40%. Most notably, both m-plane and c-plane varieties suffered severe overall efficiency degradation, by ~80%, when EBLs were not present, but with little or no efficiency degradation with increased current density. On the other hand, IQE determined by all optical resonant excitation measurements indicates negligible, if any, dependence on the presence or absence of EBL in both m-plane and c-plane varieties. Noting the presence of polarization induced field in the polar c-plane variety and the absence of it in the nonpolar m-plane variety, we can conclude that, contrary to the previous reports, the effect of polarization on carrier spillover related efficiency droop is not a dominant one. Because the relative EQE remains nearly constant for most of the current range investigated in the m-plane variety, we can also argue that the spillover is linearly proportional to the drive current.

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[1] S. Nakamura, M. Senoh, and T. Mukai, Jpn. J. Appl. Phys., Part 2 **32**, L8 (1993).
[2] T. Mukai, M. Yamada, and S. Nakamura, Jpn. J. Appl. Phys., Part 1 **38**, 3976 (1999).
[3] B. Monemar and B. E. Sernelius, Appl. Phys. Lett. **91**, 181103 (2007).
[4] I. V. Rozhansky and D. A. Zakheim, Semiconductors **40**, 839 (2006).
[5] Y. C. Shen, G. O. Mueller, S. Watanabe, N. F. Gardner, A. Munkholm, and M. R. Krames, Appl. Phys. Lett. **91**, 141101 (2007).
[6] M. H. Kim, M. F. Schubert, Q. Dai, J. K. Kim, E. F. Schubert, J. Piprek, and Y. Park, Appl. Phys. Lett. **91**, 183507 (2007).
[7] J. Hader, J. V. Moloney, B. Pasenow, S. W. Koch, M. Sabathil, N. Linder, and S. Lutgen, Appl. Phys. Lett. **92**, 261103 (2008).
[8] M. F. Schubert, J. Xu, J. K. Kim, E. F. Schubert, M. H. Kim, S. Yoon, S. M. Lee, C. Sone, T. Sakong, and Y. Park, Appl. Phys. Lett. **93**, 041102 (2008).
[9] J. Xie, X. Ni, Q. Fan, R. Shimada, Ü. Özgür, and H. Morkoç, Appl. Phys. Lett. **93**, 121107 (2008).
[10] X. Ni, Q. Fan, R. Shimada, Ü. Özgür, and H. Morkoç, Appl. Phys. Lett. **93**, 171113 (2008).
[11] Q. Dai, M. F. Schubert, M. H. Kim, J. K. Kim, E. F. Schubert, D. D. Koleske, M. H. Crawford, S. R. Lee, A. J. Fischer, G. Thaler, and M. A. Banas, Appl. Phys. Lett. **94**, 111109 (2009).
[12] X. Li, X. Ni, J. Lee, M. Wu, Ü. Özgür, and H. Morkoç, Appl. Phys. Lett. **95**, 121107 (2009).
[13] A. Niwa, T. Ohtoshi, and T. Kuroda, Appl. Phys. Lett. **70**, 2159 (1997).